

Cognitive and perceptual responses during passive heat stress in younger and older adults

Zachary J. Schlader,^{1,2} Daniel Gagnon,¹ Amy Adams,¹ Eric Rivas,^{1,3} C. Munro Cullum,⁴ and Craig G. Crandall¹

¹Institute for Exercise and Environmental Medicine, Texas Health Presbyterian Hospital Dallas, Department of Internal Medicine, University of Texas Southwestern Medical Center, Dallas, Texas; ²Department of Exercise and Nutrition Sciences, University at Buffalo, Buffalo, New York; ³Department of Kinesiology, Texas Woman's University, Denton, Texas; and ⁴Departments of Psychiatry and Neurology and Neurotherapeutics, University of Texas Southwestern Medical Center, Dallas, Texas

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Schlader ZJ, Gagnon D, Adams A, Rivas E, Cullum CM, Crandall CG. Cognitive and perceptual responses during passive heat stress in younger and older adults. *Am J Physiol Regul Integr Comp Physiol* 308: R847–R854, 2015. First published March 18, 2015; doi:10.1152/ajpregu.00010.2015.—We tested the hypothesis that attention, memory, and executive function are impaired to a greater extent in passively heat-stressed older adults than in passively heat-stressed younger adults. In a randomized, crossover design, 15 older (age: 69 ± 5 yr) and 14 younger (age: 30 ± 4 yr) healthy subjects underwent passive heat stress and time control trials. Cognitive tests (outcomes: accuracy and reaction time) from the CANTAB battery evaluated attention [rapid visual processing (RVP), choice reaction time (CRT)], memory [spatial span (SSP), pattern recognition memory (PRM)], and executive function [one touch stockings of Cambridge (OTS)]. Testing was undertaken on two occasions during each trial, at baseline and after internal temperature had increased by $1.0 \pm 0.2^\circ\text{C}$ or after a time control period. For tests that measured attention, reaction time during RVP and CRT was slower ($P \leq 0.01$) in the older group. During heat stress, RVP reaction time improved ($P < 0.01$) in both groups. Heat stress had no effect ($P \geq 0.09$) on RVP or CRT accuracy in either group. For tests that measured memory, accuracy on SSP and PRM was lower ($P < 0.01$) in the older group, but there was no effect of heat stress ($P \geq 0.14$). For tests that measured executive function, overall, accuracy on OTS was lower, and reaction time was slower in the older group ($P \leq 0.05$). Reaction time generally improved during heat stress, but there was no effect of heat stress on accuracy in either group. These data indicate that moderate increases in body temperature during passive heat stress do not differentially compromise cognitive function in younger and older adults.

cognitive function; aging; hyperthermia; thermal comfort

ADULTS OVER THE AGE OF ~ 65 YR are at an increased risk of illness, injury, hospitalization, and death during heat waves (23, 29, 33–36, 63, 64). Age-related impairments in physiological responses to heat stress undoubtedly contribute to this increased risk (32). Heat-stressed older adults have attenuated increases in skin blood flow (30, 31) and sweating (26, 27), as well as impaired cardiovascular adjustments (42, 43). However, both physiological and psychological states influence health and safety (52, 53). Thus, a variety of factors may mediate the deleterious outcomes observed in the older population during heat waves.

Healthy aging is associated with a general cognitive decline (49). Aspects of memory (4, 10, 12), attention (1, 12, 40), executive functioning (12, 58, 60), and processing speed (59) are typically [but not always (37, 48)] impaired with advancing age. This chronological cognitive decline may contribute to the risk of deleterious outcomes during heat waves in older adults by, for instance, leading to poor decision-making. Interestingly, perhaps because of the deleterious impact of heat stress on cerebral blood flow (46, 61) and/or disruptions in cerebral functional connectivity (66), many cognitive processes are impaired in heat-stressed younger adults [e.g., aspects of attention (19, 22, 65), memory (6, 19, 28, 41, 54), and executive function (16, 17, 67)], although this is not always observed (3, 50, 61). If heat stress-induced impairments in cognitive function are amplified with age, this might suggest that the contribution of cognitive factors to the risk of morbidity and mortality during heat waves would be exacerbated in older adults. However, the combined effect of heat stress and age on cognitive function remains unknown. Therefore, the purpose of this study was to test the hypothesis that indices of attention, memory, and executive function during passive heat stress will be reduced to a greater extent in healthy older, compared with younger, adults. The testing of this hypothesis will help define the role of psychological factors potentially contributing to the increased risk of morbidity and mortality during heat waves in the older population.

METHODS

Subjects

Fifteen older and fourteen younger, healthy subjects participated in this study. Each subject was fully informed of the experimental procedures and possible risks before giving informed written consent. The protocol and consent were approved by the Institutional Review Boards at the University of Texas Southwestern Medical Center at Dallas and Texas Health Presbyterian Hospital of Dallas. The subject characteristics are presented in Table 1. All subjects were nonsmokers, free of any cardiac, metabolic, neurological, or psychological diseases, and had normal, or corrected to normal, vision. Subjects taking drugs were excluded, with the exception of multivitamins and, in the older subjects only, prescription drugs for hypertension and hypercholesterolemia. Subjects were mostly right-handed, were of normal, or above normal, cognitive abilities for their age (57), and most identified themselves as being physically active.

Subjects visited the laboratory on three occasions. *Visit 1* was a familiarization trial that involved a health assessment, inclusive of vital signs (e.g., blood pressure and 12 lead ECG) and a complete health history, assessment of handedness (47), subjective levels of

Address for reprint requests and other correspondence: C. G. Crandall, Institute for Exercise and Environmental Medicine, 7232 Greenville Ave., Dallas, TX 75231 (e-mail: CraigCrandall@texashealth.org).

Table 1. *Subject characteristics*

	Younger	Older
Number of subjects	14	15
Age, yr	30 ± 4	69 ± 5*
Sex (male/female)	6/8	5/10
Height, m	1.7 ± 0.2	1.7 ± 0.1
Weight, kg	74.5 ± 19.7	74.0 ± 14.6
Body mass index, kg/m ²	25.3 ± 5.4	26.3 ± 4.1
Body surface area, m ²	1.9 ± 0.3	1.8 ± 0.2
Handedness (right/left)	13/1	14/1
Montreal Cognitive Assessment score ^a	29 ± 1	28 ± 1*
Corrected vision (yes/no)	4/10	10/5
Physical activity (high/moderate/low) ^b	7/6/1	2/11/2

Values are expressed as means ± SD. *Significantly different from younger ($P \leq 0.016$). ^aAll subjects were within the normal range for their age group [younger: ≥ 26 ; older: ≥ 23 ; (52, 53)]. ^bStratified according to Craig et al. (9).

physical activity (9), and baseline cognitive ability (44). During this visit, subjects also completed the cognitive battery one time through, and they were given the opportunity to ask questions and repeat tests that they did not fully understand. This familiarized the subjects with the tests that they completed in the subsequent experimental trials. Visits 2 and 3 comprised the experimental trials, which are described in detail below. For these trials, subjects arrived at the laboratory euhydrated (confirmed via urine specific gravity: 1.014 ± 0.008) and having refrained from strenuous exercise, alcohol, and caffeine for a period of 24 h. For premenopausal females, the experimental trials were completed within 10 days following menstruation.

Instrumentation and Measurements

Approximately 90 min prior to experimental testing, each subject swallowed a telemetry pill (HQ, Palmetto, FL), which has been shown to provide a reliable measure of central body temperature (51). Two subjects had contraindications for taking the telemetry pill. In these subjects, rectal temperature was measured at a depth ~10 cm past the anal sphincter using a general purpose thermocouple (Mon-a-therm, Mallinckrodt Medical, St. Louis, MO). Mean skin temperature was measured as the weighted average of six thermocouples attached to the skin. Body temperature was controlled via a water-perfused tube-lined suit (Med-Eng, Ottawa, ON, Canada) that covered the entire body except the head, hands, and feet. The internal-to-skin temperature gradient was calculated as the difference of internal and mean skin temperatures. Heart rate was continually recorded from an electrocardiogram (HP Patient Monitor, Agilent, Santa Clara, CA) interfaced with a cardiotelemetry (CWE, Ardmore, PA). Blood pressure was measured intermittently via auscultation of the brachial artery by electrophygmomanometry (Tango+, SunTech, Raleigh, NC), and mean arterial pressure was calculated as diastolic pressure plus 1/3 pulse pressure. Pretrial and posttrial nude body weight was also measured, providing an index of percent changes in body fluid loss.

Cognitive testing. Subjects performed six different cognitive tests from the CANTAB Eclipse battery (Cambridge Cognition, Cambridge, UK). This computerized battery, which has multiple alternate forms and established norms, has been used in multiple research settings (11, 56). The chosen CANTAB tests assess aspects of attention, memory, executive function, and subjective perceptions and required ~30–40 min to complete. Importantly, these tests have been used repeatedly in studies investigating cognitive changes in heat-stressed younger adults (16, 17, 19, 54). Subjects completed the battery of tests on five occasions: one time during *visit 1* and two times during each of the two experimental sessions. During the experimental sessions, the order of the tests within a battery was randomized, and four different versions of each test were used. The order of these different versions was quasi-randomized, such that each

subject completed all four versions. The test batteries were completed in a dimly lit, quiet, and temperature-controlled (average: $24 \pm 1^\circ\text{C}$) laboratory. Tests were performed on a rapid-response (5 ms), 43.2-cm capacitance touchscreen monitor (One World Touch, Austin, TX) that was kept at a fixed distance from each subject's eyes across both test sessions (52 ± 6 cm). For tests of reaction time, a rapid-response (1 ms) press pad was used (Cambridge Cognition, Cambridge, UK). The tests comprising the cognitive testing battery are described as follows:

Rapid visual processing test (RVP) is a measure of sustained visual attention that required ~7 min. Numbers from 2 to 9 were presented at a rate of 100 digits/min in the center of the screen in a pseudo-random order. Subjects were instructed to detect target sequences of digits (2–4–6, 3–5–7, and 4–6–8) and to register responses using the press pad. The test was delivered in two parts: a 2-min practice test stage that was not scored, and a 3-min test stage. The number of responses that occurred within 1,800 ms of the final digit presented for each of the target sequences was calculated. Outcome measures were the number of missed sequences (accuracy), mean latency (reaction time), and the number of false alarms (impulsivity).

Choice reaction time test (CRT) is a measure of attention and motor speed that requires ~7 min. A right or left pointing arrow was displayed on the screen. Subjects were instructed to press the left button on the press pad if the arrow pointed left and the right button if arrow pointed right. Subjects were instructed to respond as quickly as possible. The direction of the arrows and the delay between the arrows were presented in a random order. The test was delivered in two parts: a 24-trial practice stage and two assessment stages that comprised 50 trials each. Outcome measures were mean latency (reaction time) and the percentage of correct responses (accuracy).

Pattern recognition memory test (PRM) assesses visual memory in ~5 min. Subjects were presented with a series of 12 visual patterns one at a time every 3 s in the center of the screen. These patterns were designed so that they could not easily be given verbal labels. Following display of 12 patterns, subjects were required to choose between a pattern they had already seen and a novel pattern, the patterns were presented in reverse order. The subjects completed two 12-pattern sequences. The outcome measure was the percentage of correct responses (accuracy).

Spatial span test (SSP) is a measure of working memory that required ~5 min. Subjects were presented with a screen in which white squares were shown. Some of these squares briefly changed color in a variable sequence. Subjects were instructed to touch the boxes that changed color in the same order in which they were displayed. The number of boxes increased from two at the start of the test to nine at the end. There were three possible attempts at each level. However, as soon as the subject successfully completed a sequence at each level, they progressed to the next level. If all three sequences were unsuccessfully completed, the test was terminated. Outcome measures were the longest sequence of successfully recalled boxes (accuracy) and the total number of errors (accuracy).

One touch stockings of Cambridge test (OTS) requires executive function, spatial planning, and working memory. The duration was 10–15 min. Subjects were presented with two displays containing three colored balls. The displays were presented such that they could be perceived as stacks of colored balls held in stockings suspended from a beam. Along the bottom of the screen there was a row of numbered boxes. Subjects were initially shown how to move the balls in the lower display to copy the pattern in the upper display. The experimenter completed one demonstration problem, where the solution required one move. Then the subject completed three further practice problems, one each of two, three, and four moves. For the test itself, subjects were shown further problems, and had to mentally calculate the minimum number of moves required to solve the problems, and then to touch the corresponding box at the bottom of the screen to indicate their response. Outcome measures were the number of problems solved on the first choice and mean choices to the correct choice (accuracy), as well as mean latency to first choice and mean

latency to correct choice (response time). Data are presented for overall performance, as well as across two levels of complexity: simple: those requiring two moves, and complex: those requiring six moves, similar to that done previously (16, 17). For this latter analysis, within a testing session, each measure was obtained by averaging the score obtained over four trials.

Visual analog scales (VAS) assessed subjective indices of mood, calmness, and alertness. Duration was ~ 2 min. Sixteen questions were answered using computerized VAS. These 16 questions were grouped according to Bond and Lader (2) (100-point scales) for measures of mood (0 = good, 100 = bad), calmness (0 = calm, 100 = excited), and alertness (0 = drowsy, 100 = alert).

Immediately prior to commencing and upon terminating each cognitive battery, thermal discomfort (4 point scale: 1 = comfortable, 4 = very uncomfortable) (14), thermal sensation (7 point scale: 1 = cold, 7 = hot) (14), and affect (11 point scale: -5 = feeling bad, $+5$ = feeling good) (24) were assessed on standardized scales. The duration was ~ 30 s. To reflect average levels of these perceptions during the cognitive battery, these data are presented as a mean of perception levels before and after each cognitive testing battery.

Experimental Protocol (Visits 2 and 3)

Following instrumentation, subjects rested quietly in a semirecumbent position, while 34°C water perfused the suit. Following at least 30 min of quiet rest, baseline cognitive testing was completed, after which the subjects underwent either whole body passive heat stress or a time control period, both of which were ~ 40 – 60 min in duration (average duration – heat stress: 51 ± 5 min, time control: 52 ± 11 min, no differences between groups: $P \geq 0.518$). Whole body passive heat stress was induced by perfusing 48°C water through the suit, sufficient to increase internal temperature $\sim 1.0^{\circ}\text{C}$ above baseline, while 34°C water was perfused through the suit during the time control trial. Immediately following the heating/time control period, the subjects completed another cognitive assessment. During the heat stress trial, the temperature of the water perfusing the suit was not adjusted, thereby ensuring uncompensable heat stress and allowing internal temperature to continue rising throughout cognitive testing. This was by design, as the achievement of heat balance, independent of the magnitude of the increase in body temperature, can restore cognitive functioning (22). Whole body cooling was commenced immediately following completion of heat-stressed cognitive testing. The time control trial was utilized to ensure there was no effect of time, independent of heat stress, which might confound the interpretation of the findings during the heat stress trial. Subjects were not allowed to drink fluids at any time during either trial. Both experimental trials were conducted in a randomized manner. There were at

least 48 h between the two trials, and both trials were conducted at the same time of day.

Data and Statistical Analysis

Heart rate and thermal data were sampled continuously at 50 Hz via a data acquisition system (Biopac MP150, Santa Barbara, CA). Subject characteristics between groups were compared using independent sample *t*-tests. All other data were analyzed using mixed-model ANOVA with one between- (age) and two within- (trial, time) subject factors. These data were assessed for approximation to a normal distribution and sphericity, and no corrections were necessary. When the ANOVA revealed a significant *F* test, post hoc pair-wise comparisons were made incorporating a Bonferroni adjustment. Data were analyzed using SPSS Statistics (version 22; IBM, Armonk, NY) with a priori statistical significance set at $P \leq 0.05$. All data are reported as means \pm SD.

RESULTS

Thermal Changes

Physiological data immediately prior to cognitive testing at baseline (i.e., before heat stress or time control period), during heat stress, and following the time control period are presented in Table 2. Baseline internal and mean skin temperatures, heart rate, and mean arterial pressure were not different between groups and trials, the exception being that in the younger group baseline internal temperature was slightly, but significantly, lower (by $-0.1 \pm 0.3^{\circ}\text{C}$, $P = 0.031$) in the heat stress trial than in the time control trial. As expected, internal (by $+1.0 \pm 0.2^{\circ}\text{C}$, $P < 0.001$) and mean skin (by $+4.0 \pm 0.7^{\circ}\text{C}$, $P < 0.001$) temperatures, as well as heart rate (by $+33 \pm 12$ bpm, $P < 0.001$) increased equally ($P \geq 0.504$) between groups with heat stress, while mean arterial pressure was maintained in both groups ($P \geq 0.121$). Mean skin temperature increased slightly (by $+0.4 \pm 0.6^{\circ}\text{C}$, $P \leq 0.021$) during the time control period and was slightly lower ($P = 0.006$) in the older group at that time point. During the heat stress trial, body weight decreased ($P < 0.001$) in both groups, but the magnitude was greater ($P = 0.003$) in the younger group (Younger: $-1.2 \pm 1.0\%$, Older: $-0.6 \pm 0.8\%$). Body weight was unchanged in both groups during the time control trial (Younger: $0.0 \pm 0.2\%$, Older: $+0.1 \pm 0.5\%$).

Table 2. Physiological data immediately prior to commencing each cognitive test battery

	Heat Stress Trial		Time Control Trial	
	Younger	Older	Younger	Older
Baseline				
Internal temperature, $^{\circ}\text{C}$	$36.9 \pm 0.2^{\alpha}$	37.0 ± 0.4	37.0 ± 0.2	37.0 ± 0.3
Mean skin temperature, $^{\circ}\text{C}$	34.2 ± 0.4	33.9 ± 0.5	34.1 ± 0.2	33.8 ± 0.4
Internal-to-skin temperature gradient, $^{\circ}\text{C}$	2.6 ± 0.4	$3.1 \pm 0.5^*$	2.9 ± 0.9	3.2 ± 0.6
Heart rate, bpm	67 ± 10	68 ± 9	67 ± 11	69 ± 14
Mean arterial pressure, mmHg	86 ± 12	93 ± 10	87 ± 14	94 ± 9
Heat/Control				
Internal temperature, $^{\circ}\text{C}$	$38.0 \pm 0.2^{\dagger\alpha}$	$37.9 \pm 0.3^{\dagger\alpha}$	37.1 ± 0.2	37.0 ± 0.3
Mean skin temperature, $^{\circ}\text{C}$	$38.3 \pm 0.6^{\dagger\alpha}$	$38.4 \pm 0.6^{\dagger\alpha}$	$34.6 \pm 0.3^{\dagger}$	$34.2 \pm 0.4^{\dagger*}$
Internal-to-skin temperature gradient, $^{\circ}\text{C}$	$-0.3 \pm 0.6^{\dagger\alpha}$	$-0.4 \pm 0.7^{\dagger\alpha}$	2.5 ± 0.4	$2.8 \pm 0.5^{\dagger}$
Heart rate, bpm	$100 \pm 12^{\dagger\alpha}$	$100 \pm 16^{\dagger\alpha}$	66 ± 13	67 ± 9
Mean arterial pressure, mmHg	80 ± 12	91 ± 11	86 ± 13	98 ± 10

Values are expressed as means \pm SD. *Significantly different from younger within trial at same time point ($P \leq 0.022$). † Significantly different from baseline within trial and age group ($P \leq 0.021$). $^{\alpha}$ Significantly different from time control trial at same time point ($P \leq 0.033$).

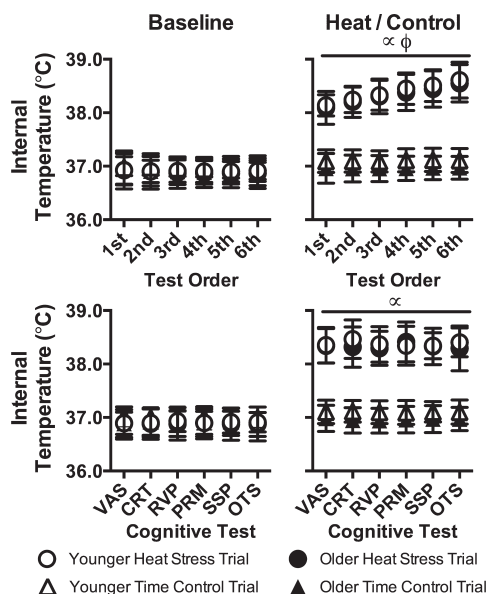


Fig. 1. Internal temperature during cognitive testing in younger ($n = 14$) and older ($n = 15$) subjects during heat stress and time control trials at baseline (left) and during heat stress (i.e., heat) and following a time control period (i.e., control; right). Top: temporal changes in internal temperature across the six cognitive tests independent of the test being undertaken. Bottom: internal temperature during each cognitive test. Data are presented as means \pm SD. VAS, visual analog scales; CRT, choice reaction time test; RVP, rapid visual processing test; PRM, pattern recognition memory test; SSP, spatial span test; OTS, one touch stockings of Cambridge test. α Significantly different from time control trial ($P < 0.001$). ϕ Significant increase over time ($P < 0.001$).

Internal temperature throughout cognitive testing is presented in Fig. 1. With the exception of heat stress cognitive testing, during which internal temperature was higher ($P < 0.001$), internal temperature was stable throughout cognitive testing ($P \geq 0.215$) and did not differ between groups ($P \geq 0.437$) or trials ($P \geq 0.236$). By design, however, internal temperature continued to rise over time ($P < 0.001$) during heat stress cognitive testing, the magnitude of which was not different between groups (Younger: $+0.6 \pm 0.3^\circ\text{C}$, Older: $+0.6 \pm 0.2^\circ\text{C}$, $P = 0.732$). Conversely, because of randomization, internal temperature during each of the six cognitive tests was not different ($P \geq 0.808$) during heat stress. At baseline, mean skin temperatures were not different ($P = 0.945$), but increased ($P < 0.001$) slightly over time during cognitive testing (by $+0.5 \pm 1.2^\circ\text{C}$), which was not different between groups ($P = 0.116$). During heat stress, mean skin temperature was higher ($P < 0.001$) during cognitive testing compared with following the time control period, and during cognitive testing, mean skin temperatures remained stable during both trials (average changes for Control: $0.0 \pm 0.5^\circ\text{C}$, Heat stress: $+0.2 \pm 0.3^\circ\text{C}$) with no differences between groups ($P \geq 0.116$). Mean skin temperature did not differ ($P \geq 0.256$) during each test within a given cognitive battery. At baseline, heart rate was stable throughout cognitive testing ($P = 0.695$) and did not differ between groups ($P = 0.444$) or trials ($P = 0.240$). Likely because of further increases in internal temperature, during heat stress, heart rate rose (by 8 ± 8 bpm) throughout cognitive testing ($P < 0.001$), and it was higher ($P < 0.001$) compared with following the time control period, but it did not differ between groups ($P = 0.785$).

Cognitive Function and Perceptual Indices

Performance on the computerized tests evaluating aspects of attention (RVP, CRT) is presented in Fig. 2. As expected, reaction time during RVP and CRT was slower ($P \leq 0.003$) in the older group. During heat stress, reaction time improved from baseline ($P \leq 0.001$) in both groups during RVP, and heat stress had no effect ($P \geq 0.094$) on RVP or CRT accuracy in either group. Performance on tests evaluating aspects of memory (PRM, SSP) is presented in Fig. 3. Overall accuracy on SSP and PRM was lower ($P < 0.001$) in the older group compared with the younger group, but there was no effect of heat stress ($P \geq 0.142$). Performance on OTS, evaluating aspects of executive function, is presented in Table 3. Overall, accuracy was lower, and reaction time was slower in the older group compared with the younger group ($P \leq 0.050$). Reaction time generally improved during heat stress, but there was no effect of heat stress on aspects of accuracy ($P \geq 0.218$). OTS performance on simple (those requiring two moves) and complex (those requiring six moves) tasks were identical to that observed for the overall performance (those requiring 1–6 moves, data not shown).

Perceptual indices are presented in Fig. 4. Heat stress increased ($P \leq 0.022$) thermal discomfort, sensations of warmth, reduced affect, worsened mood, and increased excitement, and there were no differences between groups ($P \geq 0.148$). Heat stress was associated with increased reporting of alertness, but only in the older group ($P = 0.028$).

DISCUSSION

This study tested the hypothesis that passive heat stress, sufficient to increase internal temperature 1.0 – 1.6°C (Table 2,

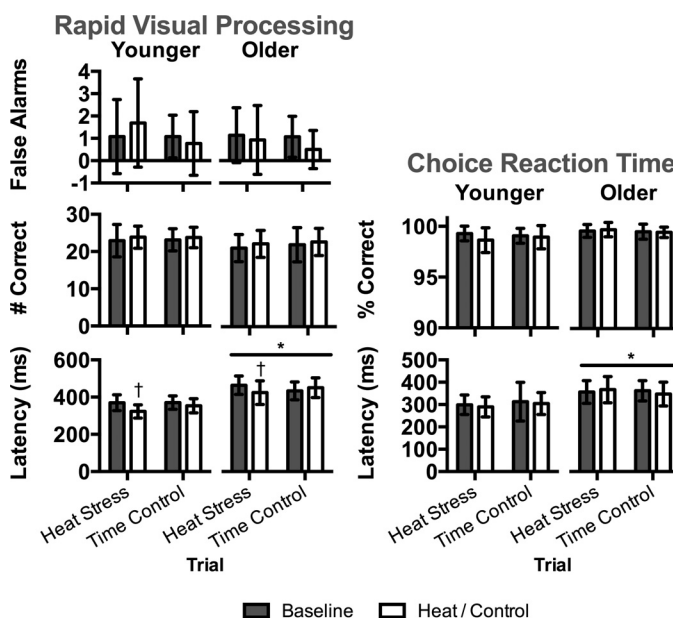


Fig. 2. Performance on tests evaluating aspects of attention in younger ($n = 14$) and older ($n = 15$) subjects during heat stress and time control trials at baseline and during heat stress (i.e., heat) and following a time control period (i.e., control). Left: rapid visual processing test (RVP). Right: choice reaction time test (CRT). Data are presented as means \pm SD. *Significantly different from younger within trial(s) at same time point(s) ($P \leq 0.003$). †Significantly different from baseline within trial and age group ($P \leq 0.001$).

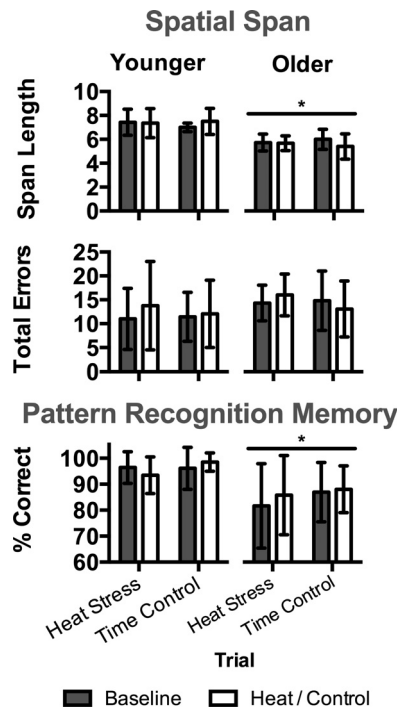


Fig. 3. Performance on tests evaluating aspects of memory in younger ($n = 14$) and older ($n = 15$) subjects during heat stress and time control trials at baseline and during heat stress (i.e., heat) and following a time control period (i.e., control). Top: spatial span test (SSP). Bottom: pattern recognition memory test (PRM). Data are presented as means \pm SD. *Significantly different from younger within trial(s) at same time point(s) ($P < 0.001$).

Fig. 1) and profoundly narrow the internal-to-skin temperature gradient (Table 2), impairs cognitive function to a greater extent in older adults. In contrast to this hypothesis, accuracy on computerized tests evaluating aspects of attention (Fig. 2), memory (Fig. 3), and executive function (Table 3) was found to be unaffected by passive heat stress in both younger and older subjects. As expected, age-related differences in processing speed (Fig. 2, Table 3), memory (Fig. 3), and executive function (Table 3) were apparent, independent of increases in body temperature. These data suggest that, independent of age, moderate passive heat stress does not impair many aspects of cognitive function, as measured by the tests used herein.

Table 3. One touch stockings of Cambridge performance

	Heat Stress Trial		Time Control Trial	
	Younger	Older	Younger	Older
Overall (1–6 moves)				
Baseline				
Problems solved on 1st choice	21.1 \pm 2.2	18.5 \pm 3.3*	21.2 \pm 2.6	19.3 \pm 2.7
Choices to correct answer	1.1 \pm 0.1	1.3 \pm 0.2*	1.2 \pm 0.2	1.3 \pm 0.3
Latency to 1st choice, s	14.4 \pm 4.6	24.2 \pm 10.1*	15.3 \pm 6.3	25.1 \pm 8.5*
Latency to correct, s	17.2 \pm 6.6	31.3 \pm 12.5*	19.5 \pm 14.8	33.9 \pm 13.6*
Heat/control				
Problems solved on 1st choice	20.9 \pm 2.5	17.9 \pm 3.2*	21.3 \pm 2.1	19.4 \pm 2.5*
Choices to correct answer	1.2 \pm 0.2	1.4 \pm 0.3* α	1.1 \pm 0.1	1.3 \pm 0.2*
Latency to 1st choice, s	10.4 \pm 3.2 \dagger	18.0 \pm 7.6* α	13.4 \pm 5.0 \dagger	21.6 \pm 9.2* \dagger
Latency to correct, s	12.1 \pm 3.6 \dagger	24.0 \pm 11.3* \dagger	16.5 \pm 8.7	27.3 \pm 13.0* \dagger

Values are expressed as means \pm SD. *Significantly different from younger within trial at the same time point ($P \leq 0.050$). \dagger Significantly different from baseline within trial and age group ($P \leq 0.049$). α Significantly different from time control trial at same time point ($P \leq 0.049$).

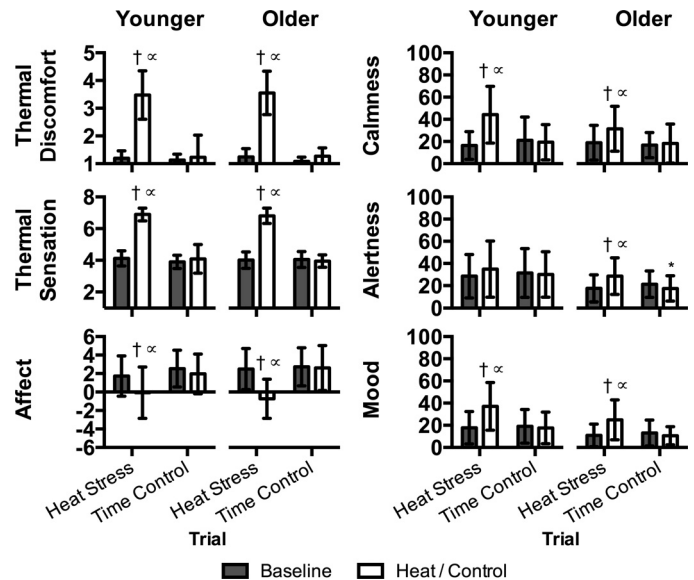


Fig. 4. Perceptual indices in younger ($n = 14$) and older ($n = 15$) subjects during heat stress and time control trials at baseline and during heat stress (i.e., heat) and following a time control period (i.e., control). Data are presented as means \pm SD. *Significantly different from younger within trial at same time point ($P = 0.049$). \dagger Significantly different from baseline within trial and age group ($P \leq 0.028$). α Significantly different from time control trial at same time point ($P \leq 0.027$).

Elevations in Body Temperature and Cognitive Function

Various aspects of attention (19, 22, 65), memory (6, 19, 28, 41, 54), and executive function (16, 17, 67) are reduced in heat-stressed younger adults. Therefore, our findings that passive heat stress did not affect the measured indices of cognitive function are unexpected (Figs. 2 and 3, Table 3). This finding is even more surprising given that performance on these exact tests was reduced in heat-stressed younger adults utilizing a similar sample size (range: 8–18 subjects), e.g., OTS (16, 17), RVP (19), PRM (19, 54), and SSP (19, 54). Thus, we are confident that our findings are not due to a lack of sensitivity, as has been speculated as a confounding factor in other similar studies (e.g., 3, 61).

It is noteworthy that in the aforementioned studies, subjects were exposed to extremely hot environments (range: 44–50°C,

30–50% RH) for 20–120 min, in which internal temperature either did not change (16, 17) or increased to a similar extent as that in the current study ($\sim 1.5^{\circ}\text{C}$) (16, 19, 54). As a result, a rationale for our divergent findings is likely the water-perfused suit method with which we induced moderate heat stress. This method was chosen given that it allows tight control of the magnitude of increases in body temperature during heat stress between groups, which allowed us to independently evaluate the effect of increases in body temperature on aspects of perception and cognitive function. This passive heat stress method resulted in increases in thermal discomfort, sensations of warmth, reductions in mood and affect (Fig. 4), and general enhancements in processing speed (reaction time) (Fig. 2, Table 3). However, it did not affect any measure of cognitive function accuracy (Figs. 2 and 3, Table 3). The rationale underlying the current observations remains unknown, especially in light of recent findings, indicating that negative affect and thermal discomfort associated with heat stress impairs aspects of executive function (specifically, OTS) (16, 19, 54). It should be noted that these decrements in aspects of executive function were observed during heat stress that induced dynamic increases in skin temperature (17), whereas mean skin temperature remained stable during the cognitive tests in the current study. As such, it may be that the potential deleterious cognitive impact of negative affect and discomfort is constrained to instances in which only skin temperature is increasing (17), as opposed to when skin temperature is stable and only internal temperature is rising (Fig. 1).

Impact of Age

Healthy aging is generally associated with reductions in aspects of memory (e.g., 17), attention (4, 10, 12), executive functioning (1, 12, 40), and processing speed (12, 58, 60). The current findings generally support this, as accuracy on the measured indices of memory (Fig. 3) and executive functioning (Table 3) were lower, and processing speed was slower (Fig. 2, Table 3) in the older group. Such findings suggest the current tests, in combination with the moderate sample size, were sensitive to cognitive differences typically associated with aging. Importantly, however, a novel aspect of this study is that age-related differences were not exacerbated with moderate increases in body temperature in the older group (Figs. 2 and 3, Table 3). Thus, the measured aspects of cognitive function were unaffected by passive heat stress in both younger and older subjects.

Aging heightens the cerebral neuronal demands of a cognitive task, and when the demand is greater than the neuronal resources available, task accuracy and reaction time are diminished (59). Interestingly, the deleterious effects of heat stress on prior assessments of cognitive function appear to be dictated by a similar mechanism, such that heat stress increases the neuronal demand of a cognitive task (39, 55) and disrupts cerebral functional connectivity (18, 25, 38). Given that passive heat stress did not affect accuracy on any of the measured aspects of cognitive function in either group, but that age-related differences persisted (Figs. 2 and 3, Table 3), it can be speculated that the neuronal demand of the cognitive tasks in the current paradigm was unaffected by the passive heat stress method utilized in this study.

The ability to perceive warm and cool temperatures is generally reduced with age (66). Furthermore, a given reduction in internal temperature elicits less thermal discomfort in older, compared with younger, adults (21). The current findings indicate that moderate passive heat stress is perceived as similarly warm and uncomfortable in both younger and older subjects (Fig. 4). Such findings were particularly surprising given that discomfort dictates the decision to initiate adaptive behavioral responses during thermal stress (e.g., change the temperature in a room, etc.) (13) and that the decision to initiate such behavior is incumbent upon greater changes in body temperature in older adults (62). Thus, it may be that older adults are less sensitive to reductions in body temperature, but sensitivity to increases in body temperature is well maintained. However, direct evidence for such an arrangement is required.

Other Considerations

Because of sweat production, dehydration typically accompanies heat stress and subsequent increases in body temperature (8, 45, 68). Notably, mild dehydration (i.e., $\leq 2\%$ body weight loss) is usually associated with impairments in various aspects of cognitive function, including aspects of attention (5), memory (7, 15, 20), and executive function (6, 7, 20). Although this study was not designed to evaluate hydration status as a modulator of cognitive function, it is notable that body weight decreased on average less than 2% in the younger and older subjects. Given that the measured aspects of cognitive function were unchanged during heat stress, which induced mild dehydration (Figs. 2 and 3, Table 3), such findings suggest that mild dehydration has little impact on attention, memory, and executive function during passive heat stress as measured herein. Interestingly, given that the magnitude of dehydration was less in the older subjects (-1.2% vs. -0.6%), it remains unknown whether dehydration during passive heat stress equally impacts cognitive function in both younger and older adults.

Perspectives and Significance

Older adults are at an increased risk of morbidity and mortality during heat waves (15, 20). Impaired physiological responses to heat stress likely contribute to this increased risk (23, 29, 33–36, 63, 64). However, given that both physiological and psychological responses dictate health and safety (32), psychological factors may also modulate the increased risk of deleterious outcomes during heat waves in the older population. The current study indicates that changes in aspects of cognitive function are not exacerbated with advancing age during heat stress. That said, during passive heat stress, classic age-related differences in aspects of cognitive function persisted. Such findings do not discount a potential cognitive contribution to the increased risk of morbidity and mortality during heat waves in the older population, but rather suggest that the cognitive contribution is not exacerbated by moderate increases in body temperature. It should also be noted that while the computerized tests used in the present study have been shown to be sensitive to abnormal cognitive function and did show the expected age-related differences, it remains to be seen whether other neuropsychological measures might prove sensitive to the hypothesized effects of heat stress. Clearly,

further studies are required to understand the multifaceted nature of this risk. Such information is important, as understanding such risk will allow for the development of interventions and countermeasures aimed at protecting the older population during heat waves.

Conclusions

The present study indicates that moderate increases in body temperature and a narrowing of the internal-to-skin temperature gradient during passive heat stress do not compromise the assessed aspects of attention, memory, or executive function in younger or older adults. That said, the expected age-related differences in cognitive performance were apparent independent of changes in body temperature. The present findings also indicate that both older and younger adults generally perceive increases in body temperature similarly.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

Author contributions: Z.J.S., C.M.C., and C.G.C. conception and design of research; Z.J.S., D.G., A.A., and E.R. performed experiments; Z.J.S. and A.A. analyzed data; Z.J.S., D.G., C.M.C., and C.G.C. interpreted results of experiments; Z.J.S. prepared figures; Z.J.S. drafted manuscript; Z.J.S., D.G., A.A., E.R., C.M.C., and C.G.C. edited and revised manuscript; Z.J.S., D.G., A.A., E.R., C.M.C., and C.G.C. approved final version of manuscript.

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